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DETERMINING SURFACE COMBATANT CHARACTERISTIC REQUIREMENTS THROUGH A MISSION EFFECTIVENESS ANALYSIS FRAMEWORK

by

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September 2007

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This research evaluates the viability to effectively determine if the ship characteristic requirements can be quantified by using Naval Sea Systems Command's Naval Battle Engagement Model (NABEM)—an agent-based simulation tool developed by Naval Sea Systems Command. In particular, we study two tactical situations by varying three platform characteristics—maximum speed, acceleration, and turning diameter—and determine how these platform characteristics affect mission performance.

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Thesis Disclaimer

The reader is cautioned that the simulation models developed in this research may not have been exercised for all possible cases of interest. While every effort has been made within the time available to ensure the models are free of computational and logic errors, they cannot be considered fully validated models. Any application of these models with out additional validation is at the risk of the user.

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EXECUTIVE SUMMARY

Ship performance characteristics, such as max-sustained speed, acceleration, and maneuverability are generally pre-determined as platform requirements based on precedents. However, these pre-determined performance characteristics have far reaching impacts on the size, logistics, manning, and cost of the ship platform. Instead of designing to pre-defined platform performance constraints, ship performance characteristics should be designated to fulfill mission objectives.

This research evaluates the viability to effectively determine if the ship characteristic requirements can be quantified by using Naval Sea Systems Command's Naval Battle Engagement Model (NABEM)—an agent-based simulation tool developed by Naval Sea Systems Command. In particular, we study two tactical situations by varying three platform characteristics—maximum speed, acceleration, and turning diameter—and determine how these platform characteristics affect mission performance.

The response surfaces generated from the NABEM simulations produced insignificant results. Maximum speed, acceleration and turning diameter produced only secondary effects. NABEM is primarily an engineering simulation model, concerned more with the detailed mathematical representation of individual systems or components. It provides a detailed representation of sensor and weapon systems, not platform characteristics. For this reason, it appeared that sensor and weapons have a stronger effect on the results, while maximum speed, acceleration and turning diameter appeared as secondary effects producing little or no effect.

Implementation of the methodology allows a designer to assess and trade-off impacts of various ship characteristics based on mission effectiveness. The methodology provides a framework where feasible and economically viable alternatives can be identified with accuracy along with their effects on mission effectiveness. While the methodology is capable of supporting the JCIDS process, NABEM was not an effective simulation tool.

Maximum speed, acceleration and turning diameter are typically tactical decisions made by the ship operator based on the current tactical situation, the "human in the loop".

If the platform sensors and weapons generate the tactical decision environment, then ship platform performance—such as maximum speed, acceleration, turning diameter—may become the dominating factors, which makes it possible to quantitatively assess their effects on mission effectiveness. Modeling human response to changing tactical situations, in relation to platform performance, is a daunting task. Such a model would greatly enhance future ability to assess ship platform characteristics on mission effectiveness and is suggested as a future research project.

I. INTRODUCTION

Ship characteristics are generally determined based on historical precedent. Characteristics such as max sustained[1] speed, signatures[2], acceleration, and maneuvering are picked based on what was done previously, unless that characteristic was proven bad or needed improvement. However, such decisions can have far reaching impacts to the platform size, lifetime logistics, manning, and cost. There must be a better way to quantitatively determine ship characteristics that directly relate the ships ability to perform its assigned mission. The objective of this work is to determine a framework that can quantify these ship characteristics as they relate to operational effectiveness.

Operational effectiveness relates operational capability to operational performance in the form of Measures of Performance metrics (MoPs). However, these MoPs must be evaluated within a specific mission and operational environment to be meaningful. The purpose of this analysis is to do just that, within the proposed framework, determine the effect specific ship characteristics have on the overall operational effectiveness during a particular mission.

A. BACKGROUND

The U.S. Navy has shifted its emphasis from design to developing broad ship and fleet architectures in order to develop design requirements to meet future fleet architectures as well as deciding on the merit of future technologies to be pursued. The establishment of the Joint Capabilities Integration and Development System (JCIDS) by the Chairman of the Joint Chiefs of Staff [13] supports this shift in emphasis. The JCIDS process requires a more system approach to determining new system development. The process is not centered on the platform or component level system, but on the integration and impact of these systems on joint/global force operations, doctrine, organization, training, personnel, material, and facilities. Assessing the impacts and effectiveness of these complex systems becomes an increasingly challenging problem. System demands,

[1] Max Sustain speed is defined as the maximum speed that can be obtained at 80% of the ships full power.

[2] Ship signatures include radar cross section, infrared signatures, and acoustic signature.

including increased performance, lower system life cycle costs, longer operating capacities, and improved productivity and efficiency, must be balanced against limited resources, scant or unknown data, the identification and resolution of conflicts, and resource allocation (people and cost).

These tradeoffs point to the need for an integrated and systematic framework that can assess system characteristics as it affects overall system effectiveness. The goal of this research was to develop an analysis framework that supports the JCIDS process by providing a methodology that provides a trade off environment that relates platform performance characteristics to operational effectives in a combat environment. This allows a sponsor to justify (quantitatively) operational, material, and technology requirements in a better/clearer framework in which to develop the systems level requirements and identify future technology investments.

B. DISCUSSION

In order to provide the proper framework in which to develop and evaluate platform performance characteristics and MoPs, a set of operational and mission requirements are generated. These requirements are in the form of Tactical Situations, which provide the operational environment, mission characteristics, goals, tasks, and threats. These tactical situations provide the framework to develop simulations to determine the MoPs, therefore relating operational effectiveness to system performance.

To ensure that the full range of possible platform characteristics are addressed, an operational effectiveness trade space is developed using a Design of Experiments (DoE) methodology coupled with a Response Surface Model (RSM).

C. OBJECTIVES

The objective of the research is developing a trade space model that relates operational effectiveness to platform performance characteristics. In addition, provide traceable linkages between measures of performance associated with individual platform characteristics, and measures of effectiveness associated with the required mission.

II. METHODOLOGY

The operational effectiveness trade space was developed in five steps: (1) defining the problem, (2) determining operational measures of performance and metrics, (3) modeling and simulation using NAVSEA's Naval Battle Engagement Model, (4) design of experiments, and (5) generating a response surface model. This approach is similar to that developed by the Aerospace Systems design Laboratory at Georgia Institute of Technology and is know as the Unified Tradeoff Environment [8][9][10][11][12][17] and assessed the impacts of system requirements on the system design trade space.

A. PROBLEM DEFINITION

In order to formulate the problem, it is assumed that there was a need for a new class of surface combatant. The Initial Capabilities Document outlines the general ship capabilities, but left several ambiguous requirements. These subjective and sometimes "fuzzy" requirements must, or should be, mapped into definitive requirements. The problem therefore is to develop an analysis framework to best determine these discrete design requirements. For this analysis three basic ship characteristics are evaluated, maximum speed, acceleration, and turning diameter. These characteristics generally have significant cost and ship systems impacts. Determining their impact on mission effectiveness would help define their relative importance to the overall ship system.

B. MEASURES OF PERFORMANCE

In order to make logical decisions and choices for the three ship characteristics, criteria to measure the value or relative importance of alternative characteristics are needed. This is an essential part of an operational effectiveness trade space, knowing what metrics are to be used to determine operational success or failure as well as how to quantify these metrics.

For this thesis the Measures of Performance (MoP) correspond to individual mission performances. Typically MoPs are quantitative and consist of a range of values

about a desired point. These values are performance metrics that the mission targets, by changing system characteristics, so as to finally achieve the qualities desired for the overall mission. MoPs are related to specific missions (i.e., tactical situations) and mission tasks.

The set of MoPs developed for each tactical situation is derived form the Universal Joint Task List (UJTL) and the Navy Tactical Task List (NTTL) [6] [7]. The UJTL and the NTTL provides relationships between missions, operations, and tasks. These relationships, along with the operational analysis, identify the operations and tasks that must be performed for mission success.

The mission establishes the requirement to perform tasks and provides the context for each task performance (including the conditions under which a task would be performed). It determines where and when a task must be performed (one or more locations). Finally, it determines the degree to which a task must be performed (implied in the concept of the operations) and provides a way to understand precisely how the performance of a task contributes to operational success.

This thesis studies two tactical situations: Tactical Situation 1, defense of a major seaport, and Tactical Situation 2, defense of a coastal convoy. Each tactical situation is designed to stress the ship characteristics under consideration. Using the UJTL and NTTL, the four general MoPs were determined to be appropriate for the analysis, Table 1.

	Units	**Measure of Performance**
M0.1	Number	Of Blue ships damaged by enemy attacks
M0.2	Number	Of Blue ship sunk by enemy attacks
M0.3	Number	Of attacking Red ships damaged.
M0.4	Number	Of attacking Red ships destroyed.

Table 1. Notional Measures of Performance

C. MODELING AND SIMULATIONS

NAVSEA's Naval Battle Engagement Model (NABEM) is used to assess the ship characteristics impacts on mission performance,. NABEM is the primary tool for the quantitative portion of this analysis. NABEM is a sophisticated Monte Carlo, time-step, many-on-many warfare model capable of accurately simulating all tactical interactions from the sea surface to the upper limit of the atmosphere (air-to-air, air-to-surface, surface-to-air, and surface-to-surface engagements). The model can handle any combination of air, surface, and shore-based platforms and associated weapons, and also includes neutral surface and air traffic (merchantmen, fishing boats, airliners, etc.) when desired.

Created in the 1970s, NABEM has been in continual use at Naval Surface Weapons Center, Carderock Division (NSWC-CD) since the 1980s. It has undergone continual development and upgrades to maintain its viability and extend its capabilities. NABEM is sensitive to a ship's radar cross section and infrared, visual, and emissions signatures in all phases of an engagement for both aircraft and anti-ship cruise missiles including detection, targeting, and lock-on. NABEM is also sensitive to ship passive protection (vulnerability) and other hull, mechanical, and electrical (HM&E) technology related issues.

The user can script the initial behavior of ships and aircraft, governing their movement, rules of engagement, EMCON status, etc. Movement can be randomized to any extent desired, allowing NABEM to vary the scenario geometry. NABEM has a limited Artificial Intelligence capability, in which both blue and red units act only on the information they possess: that is, platforms in NABEM never operate with a "gods-eye" view, as often occurs in other models. Platforms in NABEM can operate only on their situational awareness at the platform and force level, so that tactical and targeting decisions are based on the information held by each platform at each particular moment.

The model allows for the representation of the events occurring in an engagement in a Naval Tactical Data System (NTDS)-like graphics display. This capability is a valuable tool for evaluating and validating initial scenario geometry and tactics, tracing key events, troubleshooting, and demonstrating the model in briefings.

D. DESIGN OF EXPERIMENTS

The Design of Experiments (DoE) is a statistical driven process that allows for the maximization of experimental data. With a minimum number of trials (in this case simulation runs), a large number of system parameters can be quantitatively examined to understand the effect each parameter has on the overall system.

The analysis concerns the effect maximum speed, acceleration, and turning diameters have on mission effectiveness. These three parameters are the three independent input variables used for the DoE.

1. Maximum Speed

Maximum speed is varied as an independent variable; measured in knots. This variable will determine if ship speed contributes to the overall outcome of the tactical situation. The ability of the ship to provide power to maintain max speed will ultimately be compared to the outcomes of the tactical simulation to produce a response surface.

The ranges of speeds for the DoE are listed in Table 2. Max speeds were chosen to bracket current and potential surface combatant max speeds.

	Low	High
Max Speed (kts)	25.0	45.0
Acceleration (kts/sec)	0.1	0.5
Turning Diameter (ft)	1000	2500

Table 2. Speed Range of Variations

2. Acceleration

A range of acceleration is varied as independent variable; measured in knots per second. This variable determines if the ships acceleration contributes to the overall outcome of the tactical situation. The ability of the ship to provide power to accelerate will ultimately be compared to the outcomes of the tactical simulation to produce a response surface.

The ranges of accelerations for the DoE are listed in Table 2. Accelerations are chosen to bracket current and potential surface combatant accelerations.

3. Maneuvering

Turning diameter varies the ships maneuvering characteristics, measured in feet. This variable will determine if maneuvering affects the overall outcome of the tactical situation. During mission execution, the ship must make maneuvers to avoid or engage threats.

The ranges of turning diameters are listed in the Table 2. Turning diameters high and low values are based on current and potential surface combatant turning diameters.

The independent variable ranges for maximum speed, acceleration and tuning diameter represent technically feasible solutions for the ship platforms being considered. When the region of interest is the same as the region of feasibility, the best DoE model to chose is a design cube model.

There are several different design cube models to choose from, each having their own pros and cons. For this analysis a face-center central composite design was chosen. The face-center central composite design is an efficient design that is ideal for sequential experimentation and allows a reasonable amount of information for testing of model fit while not involving an unusually large number of design points.

Each DoE, one for Tactical Situation 1 and one for Tactical Situation 2 systematically varies these three independent variables, Table 3.

Design Points	Max Speed (kt)	Acceleration (kt/sec)	Turn Dia (ft)
1	25	0.5	1000
2	45	0.5	1000
3	45	0.3	1750
4	45	0.1	1000
5	25	0.5	2500
6	45	0.1	2500
7	35	0.1	1750
8	25	0.3	1750
9	25	0.1	1000
10	35	0.3	1750
11	35	0.5	1750
12	45	0.5	2500
13	35	0.3	1000
14	35	0.3	2500
15	25	0.1	2500

Table 3. Design of Experiments Independent Variables

Each design point is simulated in NABEM for 5000 independent runs. The resulting statistics from each design point provides the operational/mission effects or MoPs related to the variations in ship characteristics

E. RESPONSE SURFACE MODEL

The RSM is a multi-variable regression technique that models the response of a complex system using a simple equation. The response surface is modeled using a second-order quadratic equation thus giving a model of the relationships between the independent (input) variables and the responses obtained for the simulation model, in this case NABEM. The response surface is modeled using a second-order quadratic equation and is expressed as

$$R = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j$$

Where:
b_i are the regression coefficients for the first-degree terms.
b_{ij} are the coefficients for the cross-product terms.
x_i and x_j are the design variables.
b_{ii} are the coefficients for the pure quadratic terms.

The RSM is generated using data provided by the DoE and the NAMBEM simulations. This data is fed into SAS's JMP software to generate the RSM. JMP (Version 5.1) is a statistical analysis software tool that links statistics with graphics to interactively explore, understand, and visualize data. The software is designed to uncover relationships and outliers in the data. JMP provides statistical tools as well as Design of Experiments and Statistical Quality Control. JMP's built-in capabilities are used to develop the DoE, the RSMs, and JMP's interactive graphic tools to explore the design space. In particular JMP's profiler, contour profiler, and surface graphic displays are used.

F. ANALYSIS OF RESPONSE SURFACE MODEL

The response surfaces, of RSM, form the basis or framework of the operational effectiveness trade space model. Through visualization tools built into the analysis tool (JMP), the trade space can be analyzed. The results are displayed through a series of visualization tools, prediction and contour profilers, and response surface plots. The profiler plots displays prediction traces (predicted responses as one variable is changed while holding the others constant) for each variable. The response surface plots provide a quick visual of how the response functions are behaving.

The prediction profiler isolates the impact of every factor for every response. The contour profiler illustrates interaction of one or several of the variables have on one another. The prediction and contour profilers are interactive plots, therefore, very difficult to show in a written report. Therefore, only the general ship characteristics effects on mission performance are described for each tactical situation.

G. ASSUMPTIONS AND CAVEATS

A conceptual surface combatant is developed specifically for this study and does not relate to any program of record or any potential U.S. Navy program. This conceptual ship is designated as the Small Surface Combatant (SSC) for this analysis. Mission systems for the SSC were modeled to be consistent with current or projected systems and are constant and consistent throughout the different tactical situations. To maintain the unclassified natural of this thesis, sensor and weapon performance data is generated from

open source literature. It should be noted that the intent of the analysis is not to evaluate mission systems performance or to compare individual mission system capabilities, performance, or effectiveness. The focus of the analysis is to determine the effect of specific ship characteristics on the ship's overall mission performance.

The Red Force combat systems and platforms are chosen to be representative of likely current and future threats; again data is obtained from open source resources.

The tactical situations reflect missions that stress the ship characteristics being evaluated. They are designed to resemble possible real world situations, but the locations of these scenarios are kept generic to maintain the unclassified nature of this analysis.

NABEM is a good combat simulation model; however, like most simulation models it has its limitations. One of these limitations is that the simulation has to be well scripted, not allowing for a human in the loop decisions as to course, speed, weapons to use, etc. that can determine the outcome of a simulation.

Blue force platforms does not include helicopter capability and is not included in the NABEM simulation.

III. TACTICAL SITUATION 1

Tactical Situation 1 (TS1) models the defense of a major seaport against enemy forces trying to gain entry into the port. Blue force's mission is to prevent enemy forces (Red Force) from gaining access to the port. The port of San Francisco is chosen for this tactical situation.

Blue forces are deployed at the mouth and within San Francisco harbor in preparation of Red hostilities. Three blue small surface combatants are assigned a patrol area each. Two patrol the approaches to the harbor, while the third patrols the inner harbor area, as shown in Figure 1. Figure 2 shows the TS1 scenario as modeled in NABEM.

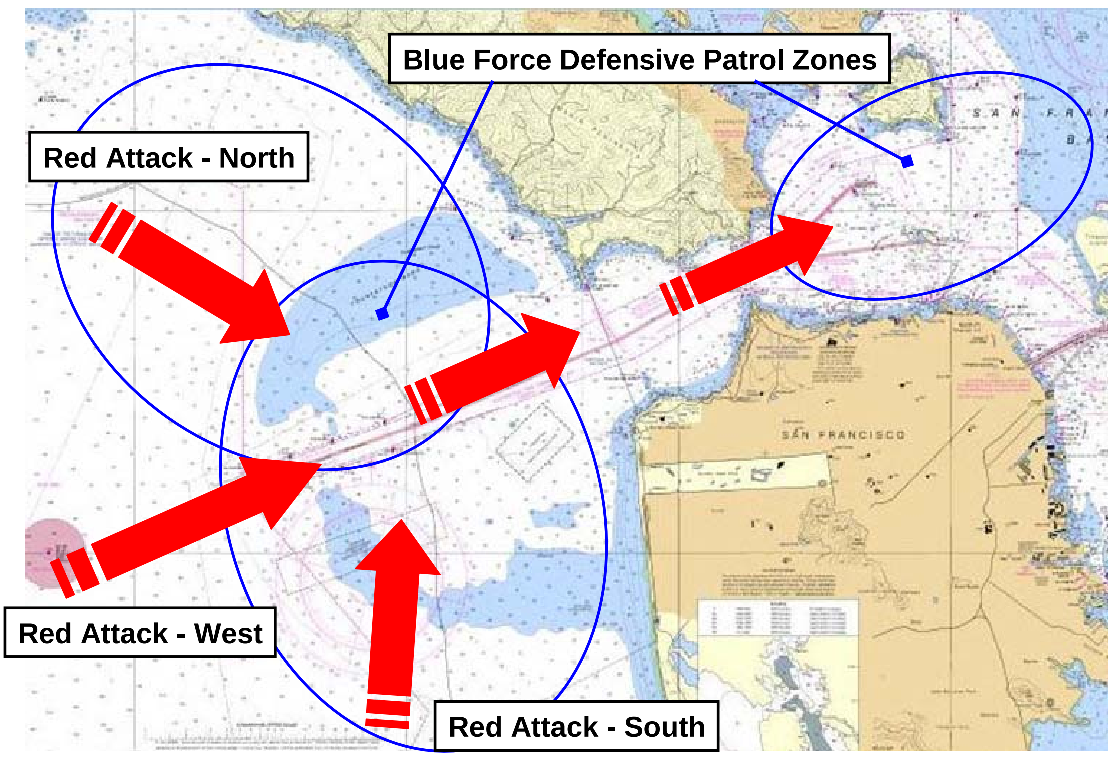

Figure 1. TS1 General Laydown

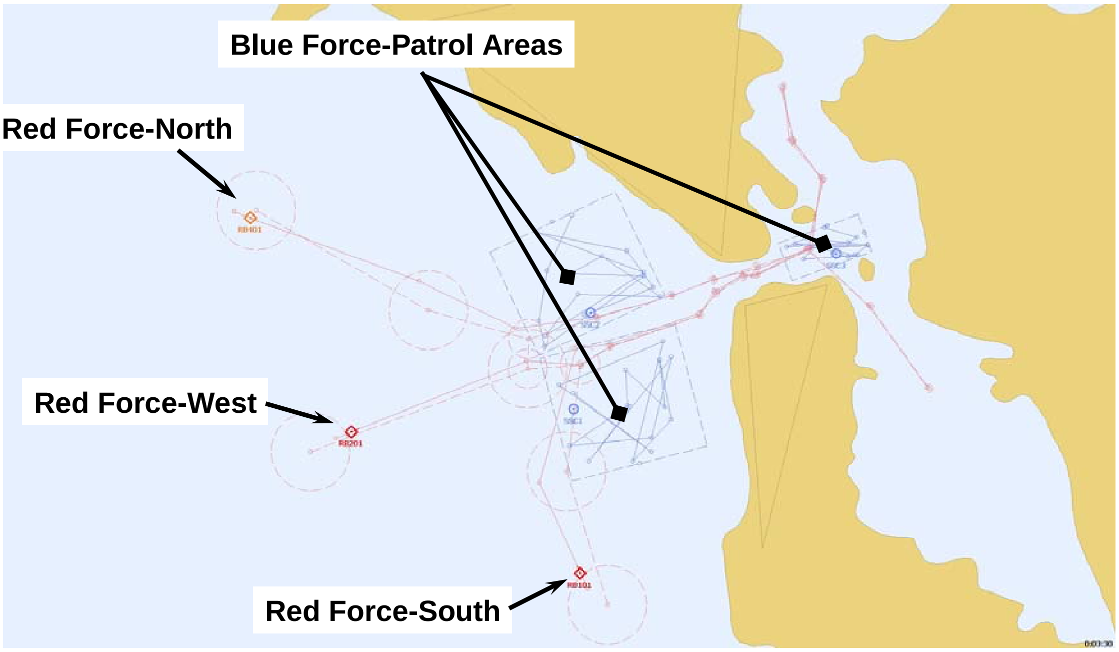

Figure 2. TS1 NABEM Model Laydown

The red force comprises three separate squadrons, each squadron approaching the harbor from different directions, as shown in Figure 1. The north and the south squadrons had three high speed attack craft, while the western squadron had six. The mission goal for Red Forces goal is to penetrate the harbor defenses and disrupt harbor operations.

A. RED FORCE

The red force is chosen to be representative of the likely threat for this tactical situation. Each red force platform, designated as Red PTG, was modeled as a small fast attack craft with operating characteristics similar to the Peoples Republic of China Type 083 Fast Attack craft and the Iranian Navy's Bohammer fast attack craft. Red PTG has a maximum speed of 35 knots, 20.0 nautical mile range navigational radar, and an ESM detection system.

Each Red PTG carries six short-range missiles. Each missile has a maximum operating range of approximately 2.0 nautical miles and has similar operating characteristics to hand-launched anti-armor missiles and rocket propelled grenades.

B. BLUE FORCE

Blue forces consist of three small surface combatants, designated as Blue SSC. Each Blue SSC platform is modeled as a corvette size combatant similar to the German Type 143 and 148 Fast Attack Craft and the Swedish Goteborg Class Corvettes. Blue SSC forms the basis for the design of experiments in which max speed, accelerations and turning diameter are varied.

Each Blue SSC has a medium caliber gun (similar to the Mk 57 Naval Gun), 24 short range missiles, a point defense gun (similar to the Mk 15 CIWS), an ESM detection and decoy system, and a 200 nautical mile surface search radar (similar to a SPY-1F radar).

C. METRICS FOR TACTICAL SITUATION 1

The MoPs chosen for TS1 reflect measurable mission characteristics that are influenced by the three ship characteristics being investigated (Table 4). The metrics are designed to evaluate the effectiveness of the Blue Forces against the threat in each particular scenario.

	Units	**Measure of Effectiveness**
M1.1	Number	Red PTGs Survive and Enter Harbor
M1.2	Number	Blue SSCs Sunk
M1.3	Number	Blue SSCs Damaged

Table 4. Measures of Effectiveness for TS1

D. ANALYSIS FOR TACTICAL SITUATION 1

The DoE is run in NABEM according to the DoE matrix in Table 3. There are 15 design points; each design point is simulated 5000 times, each with the initial simulation parameters randomly chosen. The simulations results are listed in Table 5. Response surface models for each MoE are generated from the results listed in Table 5. Each response is checked for RSquare values, Adjusted RSquared values, F statistics, and Model Fit Error to ensure the accuracy of the model fit. If any of the checks fails, it is an

indication that the basic second-order model is not appropriate for the response. In these cases two options are available to provide a better fit, adding higher terms or adding more design points. For all the MoEs only one of the checks fail, Model Fit Error. Higher order terms are tried, but fail more than one of the checks. Generating more design points was considered, but due to time and resources was not possible. For this thesis the response surface models generated from the design points in Table 6 are the best fit possible. For a more thorough examination the TS1's response model are referred to Appendix A.

E. RESULTS

Design Points	Max Spd	Accel	Turn Dia	PTGs Enter Harbor		SSCs Sunk		SSCs Damaged	
	(kt)	(kt/sec)	(ft)	Mean	% of Total	Mean	% of Total	Mean	% of Total
1	25	0.5	1000	0.979	(8.2)	0.330	(11.0)	1.141	(38.0)
2	45	0.5	1000	1.149	(9.6)	0.413	(13.8)	1.410	(47.0)
3	45	0.3	1750	1.224	(10.2)	0.392	(13.1)	1.404	(46.8)
4	45	0.1	1000	1.202	-10	0.404	(13.5)	1.421	(47.4)
5	25	0.5	2500	1.021	(8.5)	0.317	(10.6)	1.124	(37.5)
6	45	0.1	2500	1.161	(9.7)	0.382	(12.7)	1.424	(47.5)
7	35	0.1	1750	0.883	(7.4)	0.377	(12.6)	1.299	(43.3)
8	25	0.3	1750	0.998	(8.3)	0.320	(10.7)	1.157	(38.6)
9	25	0.1	1000	0.857	(7.1)	0.313	(10.4)	1.170	(39.0)
10	35	0.3	1750	0.926	(7.7)	0.365	(12.2)	1.304	(43.5)
11	35	0.5	1750	0.938	(7.8)	0.334	(11.1)	1.137	(37.9)
12	45	0.5	2500	1.217	(10.1)	0.393	(13.1)	1.401	(46.7)
13	35	0.3	1000	0.924	(7.7)	0.377	(12.6)	1.281	(42.7)
14	35	0.3	2500	0.936	(7.8)	0.370	(12.3)	1.305	(43.5)
15	25	0.1	2500	0.926	(7.7)	0.319	(10.6)	1.113	(37.1)

Table 5. Final Results for TS1

From the response surface model for each MoE a prediction profiler plot is generated which shows the interrelationships between all the parameters, as shown in Figure 3. The prediction profiler serves as the principal tool for evaluating the individual responses. The following sections discuss the key findings for each of the ship characteristics investigated.

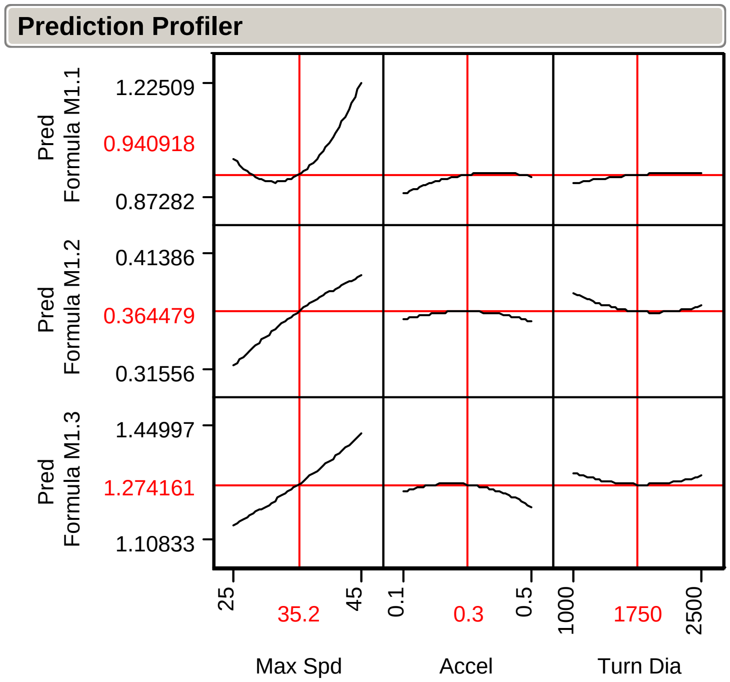

Figure 3. Prediction Profiler Results for TS1

1. Max Speed

Referring to the prediction profiler in Figure 3; as maximum speed increases all three MoEs increase. Meaning, as Blue SSC's speed increases the number of Red PTGs successfully entering the harbor also increases, and so does the number of SSCs damaged or sunk. This behavior seems to contradict general conventional rules of thumb, but as speed increases, Blue SSCs are exposed to more Red PTGs. So why then does the number of PTGs surviving go up and not down with similar weapons and sensors. Simple Red PTGs outnumber the Blue SSCs by 4 to 1. Therefore, there is a higher probability that Blue will incur damage or sink. With fewer Blue ships available the probability that more PTGs survive to complete their mission (enter the harbor) increases. Another factor to consider, as modeled in the simulation, Blue SSCs have a limited amount of ready service ammunition. As Red PTGs attack, Blue deplete their ready

service ammunition. The simulation model reloads ammunition over time and this time delay is a contributing factor to the increased number of Blue SSCs damaged or sunk.

While maximum speed has an effect on the outcome of the tactical situation, the effect is insignificant.

2. Acceleration

Referring to the prediction profiler in Figure 3, as acceleration increases, the number of Blue SSCs sunk or damaged (M1.2 and M1.3) tend to decrease and the numbers of Red PTGs survive to enter the harbor (M1.1) increase. This behavior seems to contradict general conventional rules of thumb. However, tactical situation 1 iss set in a very confined operating space (San Francisco Harbor) negating possible advantages acceleration might provide in an open ocean operational area. In addition, the increase or decrease in acceleration effects on the MoE are very small compared to the other ship characteristics. Combined the overall effect from acceleration is negligible.

3. Turn Diameter

Referring to the prediction profiler in Figure 3, as the turning diameter increases, the number of Blue SSCs sunk or damaged (M1.2 and M1.3) tend to decrease and the number of Red PTGs survives to enter the harbor (M1.1) increase. This behavior also seems to contradict general conventional rules of thumb. However, the initial turning diameter of 1000 ft produces a high number of Blue SSCs damaged or sunk. This is consistent with the results when maximum speed is increased. A highly maneuverable ship in confined waters increases the probability of exposure to enemy weapons, therefore increasing the probability of damage or sinking Blue SSCs. Factor in the Red PTGs four to one superiority in numbers the results can be understood. These effects are very small and are insignificant.

F. CONCLUSIONS

The final response surface models developed for tactical situation 1 produced tangible models that link ship characteristic to mission effectiveness; however, the effects are small and insignificant. NABEM is primarily an engineering simulation model,

concerned more with the detailed mathematical representation of individual systems or components. NABEM provides a detailed representation of sensor and weapon systems, not platform characteristics. For this reason sensor and weapons effects dominate the results. Maximum speed, acceleration and turning diameter appear as secondary effects producing little or no impact to the overall outcome of the tactical situation.

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IV. TACTICAL SITUATION 2

Tactical Situation 2 (TS2) models the defense of a blue convoy transiting through a wide strait off the coast of Blue territory. Red forces attack the convoy from two different directions and at different times. For this tactical scenario the Straits of Florida is modeled, with the Blue convoy, comprised of ten merchant ships, transiting north through the straits, as shown in Figure 4. Figure 5 shows the TS2 scenario as modeled in NABEM.

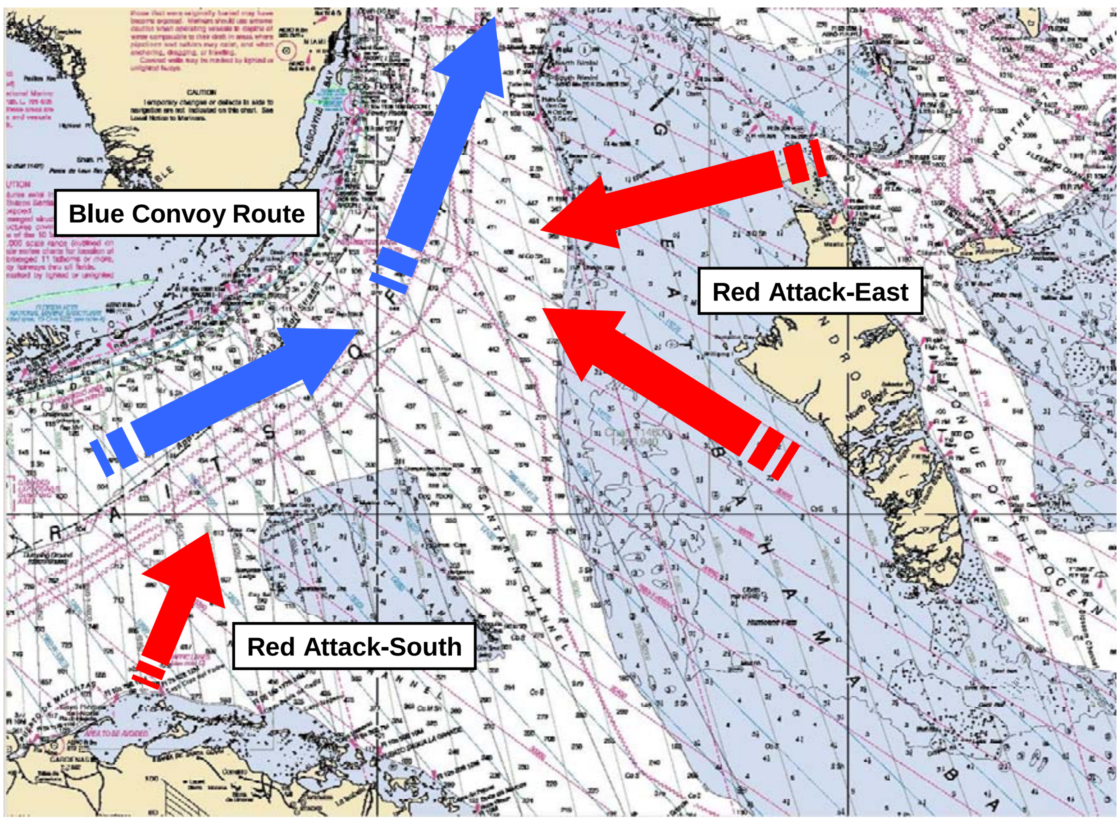

Figure 4. TS2 General Laydown

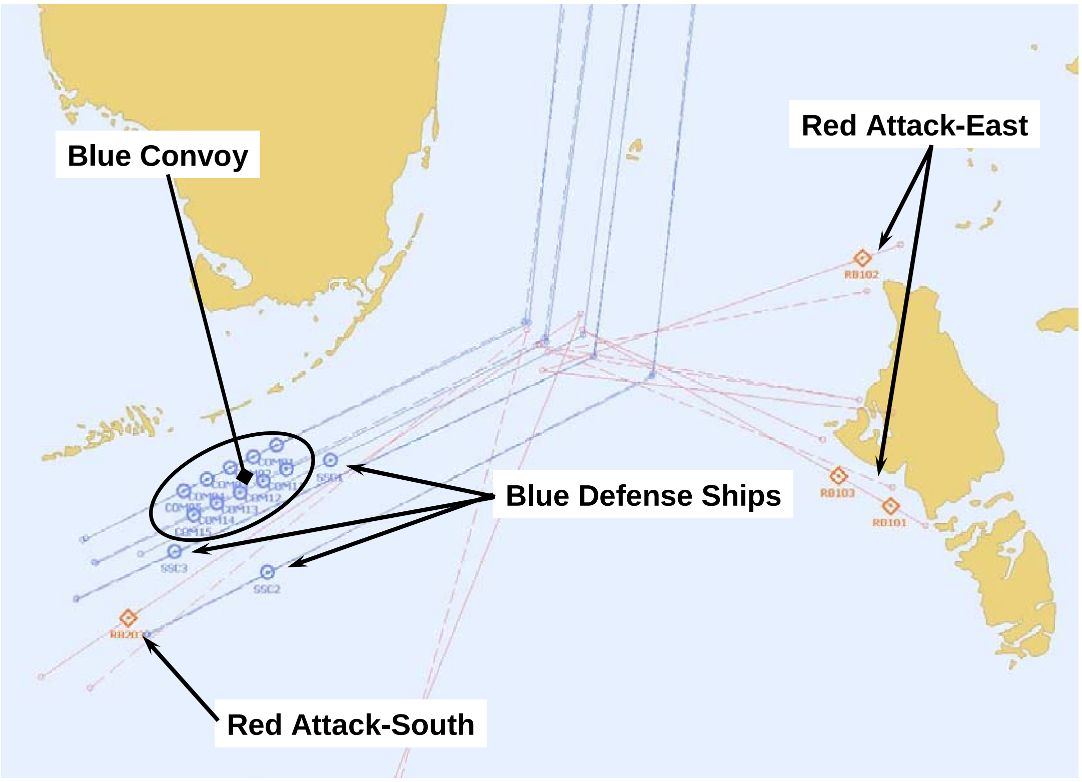

Figure 5. TS2 NABEM Model Laydown

The red force attacks the blue convoy from two different directions. First, a single Red ship attacks the convoy from the rear, hoping to draw the two Blue combatants away from the convoy. The second attack of four Red ships comes from the east and aims at the lead ship of the convoy, as shown in Figure 4.

A. RED FORCE

The red force is chosen to be representative of the likely threat for this tactical situation. Each red force platform, designated as Red PTG, was modeled as a small fast attack craft with operating characteristics to Peoples Republic of China Type 083 Fast Attack craft with a maximum speed of 35 knots, 20 nautical mile range navigational radar, and an ESM detection system.

Each Red PTG carries six short-range missiles. Each missile has a maximum operating range of approximately 6.0 nautical miles and similar operating characteristics to the Hellfire missile.

B. BLUE FORCE

Blue forces consist of three small surface combatants, designated as Blue SSC. Each Blue SSC platform is modeled as a corvette size combatant similar to the Swedish Goteborg Class Corvettes. Blue SSC forms the basis for the design of experiments in which max speed, accelerations and turning diameter are varied.

Each Blue SSC has a medium caliber gun (similar to the Mk 57 Naval Gun), 24 short range missiles, a point defense gun (similar to the Mk 15 CIWS), an ESM detection and decoy system, and a 200 nautical mile surface search radar (similar to a SPY-1F radar).

Blue force convoy ships are modeled as typical coastal commercial tankers and were designated as Blue Tankers.

C. METRICS FOR TACTICAL SITUATION 2

The measures of performance for TS2 reflect measurable mission metrics that are influenced by the three ship characteristics being investigated, as shown in Table 6. The metrics are designed to evaluate the effectiveness of the Blue Forces against the threat in each particular scenario.

	Units	**Measure of Effectiveness**
M2.1	Number	Of Blue SSCs damaged by enemy attacks
M2.2	Number	Of Blue SSCs sunk by enemy attacks
M2.3	Number	Of Blue Tankers sunk by enemy attacks
M2.4	Number	Of attacking Red PTG sunk

Table 6. Measures of Effectiveness for TS2

D. ANALYSIS FOR TACTICAL SITUATION 2

The DoE is run in NABEM according to the DoE matrix in Table 3. There are 15 design points; each design point was simulated 5000 times, each with the initial simulation parameters randomly chosen. The results from the simulations are listed in Table 7. A response surface model is generated from the results in Table 7. Each

response is checked for RSquare values, Adjusted RSquared values, F statistics, and Model Fit Error to ensure the accuracy of the model fit. If any of the checks fail, it is an indication that the basic second-order model is not appropriate for the response. In these cases two options were available to provide a better fit, adding higher terms or adding more design points. For all the MoEs at least one of the checks failed. Higher order terms were tried for all the design points. Adding [Turn Diaemeter^2 x Acceleration] to M2.1 and [Max Speed^2 x Acceleration] to M2.3 makes it possible to pass three of the four checks, but all the response surface model still fail one check, Model Fit Error. Generating more design points was considered, but due to time and resources was not possible. For this thesis the response surface models from the design points in Table 7 are the best fit possible. For a more thorough examination the TS2's model fit, see Appendix B.

E. RESULTS

Design Points	Max Spd	Accel	Turn Dia	Blue SSCs Damaged		SSCs Sunk		Tankers Sunk		Red PTG Sunk	
	(kt)	(kt/sec)	(ft)	Mean	% of Total	Mean	% of Total	Mean	% of Total	Mean	% of Total
1	25	0.5	1000	0.397	(13.3)	0.181	(6.0)	0.338	(3.4)	2.374	(59.4)
2	45	0.5	1000	0.432	(14.4)	0.228	(7.6)	0.205	(2.1)	3.449	(86.2)
3	45	0.3	1750	0.461	(15.4	0.221	(7.4)	0.203	(2.0)	3.431	(85.8)
4	45	0.1	1000	0.351	(11.7)	0.190	(6.3)	0.205	(2.1)	3.495	(87.4)
5	25	0.5	2500	0.582	(19.4)	0.238	(7.9)	0.337	(3.4)	2.376	(59.4)
6	45	0.1	2500	0.384	(12.8)	0.177	(5.9)	0.206	(2.1)	3.480	(87.0)
7	35	0.1	1750	0.344	(11.5)	0.165	(5.5)	0.230	(2.3)	2.937	(73.4)
8	25	0.3	1750	0.545	(18.1)	0.219	(7.3)	0.338	(3.4)	2.379	(59.5)
9	25	0.1	1000	0.402	(13.4)	0.184	(6.1)	0.345	(3.5)	2.382	(59.5)
10	35	0.3	1750	0.458	(15.3)	0.201	(6.7)	0.233	(2.3)	2.886	(72.2)
11	35	0.5	1750	0.577	(19.2)	0.208	(6.9)	0.342	(3.4)	2.347	(58.7)
12	45	0.5	2500	0.564	(18.8)	0.263	(8.8)	0.214	(2.1)	3.383	(84.6)
13	35	0.3	1000	0.408	(13.6)	0.177	(5.9)	0.245	(2.4)	2.912	(72.8)
14	35	0.3	2500	0.483	(16.1)	0.216	(7.2)	0.223	(2.2)	2.845	(71.1)
15	25	0.1	2500	0.520	(17.3)	0.213	(7.1)	0.356	(3.6)	2.330	(58.2)

Table 7. Final Results for TS2

From the response surface model for each MoE a prediction profiler plot is generated which shows the interrelationships between all the parameters, Figure 6. The prediction profiler serves as the principal tool for evaluating the individual responses.

The following sections discuss the key findings for each of the ship characteristics investigated.

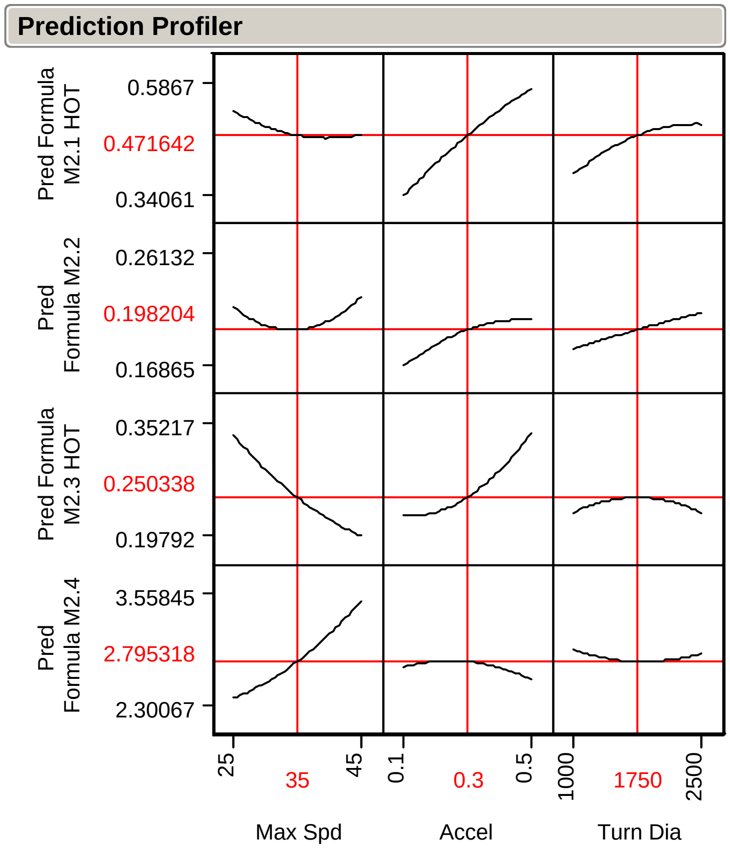

Figure 6. Prediction Profiler Results for TS2

1. Max Speed

Referring to the prediction profiler in Figure 6, maximum speed has an overall positive effect. As maximum speed increases the number of Blue Tankers sunk (M2.3) decrease and the number of PTGs sunk (M2.4) increase. This makes sense, as the number of PTGs goes down, so should the number of Tankers sunk because the Tankers are exposed to fewer PTGs and thus lowers the probability of the tankers getting sunk.

However, as maximum speed increases, the number of Blue SSCs damaged or sunk (M2.1 and M2.2) increase. The explanation for this is, as speed increases Blue SSCs are exposed to more potential combat with Red PTGs, increasing the number of

Red PTGs sunk, but which also increases Blue SSCs exposure to Red weapons, increasing the probability of Blue SSCs getting damaged or sunk.

While maximum speed has an effect on the outcome of the tactical situation, the effect is insignificant.

2. Acceleration

Referring to the prediction profiler in Figure 6, acceleration has an overall negative effect on Blue forces. As acceleration increases the number of Blue SSCs and Tankers sunk or damaged increase. But the number of Red PTGs sunk trends to decrease. This appeared to be a contradiction, but as more PTGs survive, more Blue ships are exposed to enemy fire, thus have a higher probability of getting damaged or sunk. Therefore, increasing the ship's acceleration would increase the number of PTGs sunk, but in this instance the change is so small that it can be ignored.

3. Turn Diameter

Referring to the prediction profiler in Figure 6, turning diameter has a positive effect on the number Blue SSCs damaged or sunk and the number of Blue Tankers sunk (M2.1, M2.2, and M2.3). Also, as turning diameter gets tighter the number of Red PTGs sunk goes up initially, the plot for turning diameter for M2.4 as a concave structure indicating for a turning diameter of approximately 1750 ft the numbers of PTGs sunk are at a minimum. The model suggests that turning diameter was beneficial to the outcome of Blue forces, but these benefits are small. The small changes in the number of Red PTGs sunk are not significant.

F. CONCLUSIONS

The final response surface models developed for tactical situation 2 produced tangible models that link ship characteristic to mission effectiveness; however the effects are small and insignificant. NABEM is primarily an engineering simulation model, concerned more with the detailed mathematical representation of individual systems or components. NABEM provides a detailed representation of sensor and weapon systems,

not platform characteristics. For this reason sensor and weapons effects dominated the results. Maximum speed, acceleration and turning diameter appear as secondary effects producing little or no impact to the overall outcome of the tactical situation.

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V. CONCLUSIONS

Response surfaces generated from the NABEM simulations produce insignificant results. Maximum speed, acceleration and turning diameter produce only secondary effects, while sensor and weapons effects dominate the results. NABEM is primarily an engineering simulation model, concerned more with the detailed mathematical representation of individual systems or components. It provides a detailed representation of sensor and weapon systems, not platform characteristics. For this reason sensor and weapons effects dominates the results, while maximum speed, acceleration and turning diameter appeared as secondary effects producing little or no effect.

Implementation of the methodology allows a designer to assess and trade-off impacts of various ship characteristics based on mission effectiveness. The methodology provides a framework where feasible and economically viable alternatives can be identified with accuracy along with their effects on mission effectiveness. While the methodology is capable of supporting the JCIDS process, NABEM is not an effective simulation tool to use in the process.

Maximum speed, acceleration and turning diameter are typically tactical decisions made by the ship operator based on the current tactical situation, the “human in the loop”. If the platform sensors and weapons generate the tactical decision environment, then ship platform performance—such as maximum speed, acceleration, turning diameter—may become the dominating factors, which makes it possible to quantitatively assess their effects on mission effectiveness. Modeling human response to changing tactical situations, in relation to platform performance, is a daunting task. Such a model would greatly enhance future ability to assess ship platform characteristics on mission effectiveness and is suggested as a future research project.

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APPENDIX A RESPONSE SURFACE MODEL FOR TACTICAL SITUATION 1

The following sections provide the general procedures to develop the response surface model fits for each measure of effectiveness for tactical situation 1. All analysis work is preformed using SAS's statistical modeling tool JMP (Version 5.1).

A. FIT FOR M1.1

The results for the NABEM tactical situation 1 simulation for M1.2 MoE arre feed into JMP. The fit model option is used to do an initial fit of the data using the surface response option.

First is to determine if the model statistics indicate a good fit to the data. One, the RSquared and RSquared Adjusted values are 0.988 and 0.967 respectively, Figure A1 Generally anything higher than 0.80 would be acceptable and indicates a good model fit. Two, the Analysis of Variance the F statistic is 0.0003, which is well below the 0.05 for a desired 95% confidence level. The basic model statistics look good.

Second, a review of two key plots is preformed. One, the Actual by Predicted Plot, Figure A1, all the data points are falling within the 95% confidence lines (the dashed red line), again indicating a good fit to the data. Two, the Residual by Predicted Plot, Figure A2, shows a fairly evenly shattering of the points. Some areas in the plot have holes, but that can be attributed to the small data set being analyzed, otherwise everything indicates a good model fit.

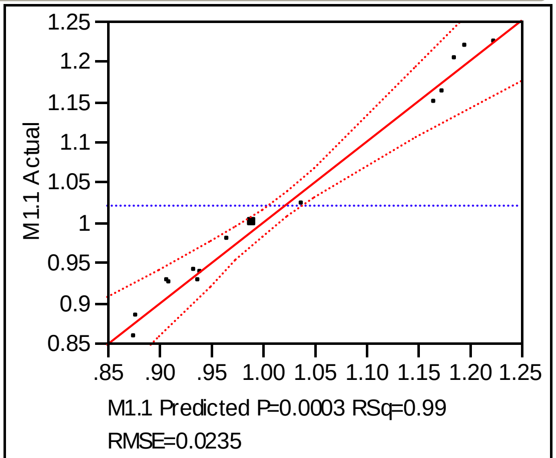
All indications show that the model listed in the Parameter Estimates in Figure A1 is a good model fit to the data. One additional test is needed to verify the accuracy of the model, a model fit error analysis.

The model fit error analysis checks how well the model fits the data points from the design of experiments. The model fit error, measured as the model percent error, is determined for each data point and the resulting distribution is evaluated against two error distribution criteria; a mean of approximately 0.0 and a standard deviation of less than 1.0 are desired. The model percent error is computed for each using the following equation:

$$\{[(\text{Predicted Value}) - (\text{M1.1 Actual})] / (\text{M1.1 Actual})\} \times 100$$

Figure A3 shows the resulting distribution for the model percent error. The distribution does not look like a normal distribution, which is what would be expected. In addition, the mean is 0.017, which is close to 0.0, but the standard deviation is 1.39, which is higher than desired. Based on the model fit error analysis, the model for M1.1 does not perform as well as would be expected from the initial analysis of the fit. This is due most likely to the small data set used for the analysis. An additional set of data points should be added to the analysis, to help better define the model. However, due to time and limited resources, that is not possible, and the fit will have to suffice with the caveat that the final analysis can only provide general trends, not qualitative answers.

Actual by Predicted Plot



Summary of Fit

RSquare	0.988398
RSquare Adj	0.967514
Root Mean Square Error	0.023519
Mean of Response	1.022707
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	0.23562197	0.026180	47.3289
Error	5	0.00276578	0.000553	Prob > F
C. Total	14	0.23838775		0.0003

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.2018056	0.18119	12.15	<.0001
Max Spd	-0.100403	0.010549	-9.52	0.0002
Accel	0.9544208	0.283497	3.37	0.0200
Turn Dia	0.0001225	0.000101	1.21	0.2797
Max Spd*Max Spd	0.0016942	0.000147	11.55	<.0001
Max Spd*Accel	-0.013388	0.004158	-3.22	0.0235
Accel*Accel	-0.780833	0.366671	-2.13	0.0865
Max Spd*Turn Dia	-0.000001	0.000001	-1.27	0.2614
Accel*Turn Dia	0.0000692	0.000055	1.25	0.2674
Turn Dia*Turn Dia	-2.113e-8	2.607e-8	-0.81	0.4546

Figure A1. Summary of Model Fit For M1.1

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Max Spd	1	1	0.05010935	90.5882	0.0002
Accel	1	1	0.00626944	11.3340	0.0200
Turn Dia	1	1	0.00081246	1.4688	0.2797
Max Spd*Max Spd	1	1	0.07380516	133.4257	<.0001
Max Spd*Accel	1	1	0.00573521	10.3682	0.0235
Accel*Accel	1	1	0.00250848	4.5349	0.0865
Max Spd*Turn Dia	1	1	0.00088621	1.6021	0.2614
Accel*Turn Dia	1	1	0.00086112	1.5568	0.2674
Turn Dia*Turn Dia	1	1	0.00036312	0.6565	0.4546

Residual by Predicted Plot

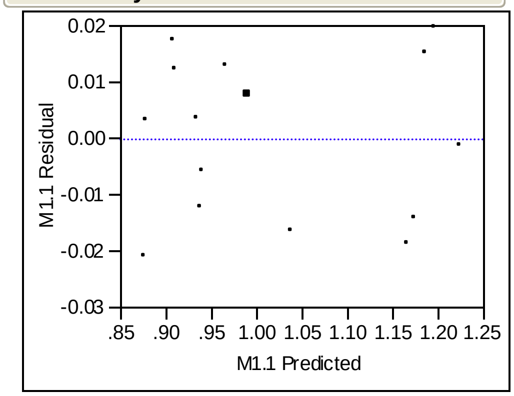
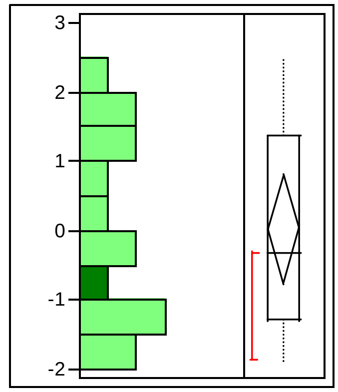


Figure A2. Summary of Model Fit For M1.1 (continued)

Error M1.1



Quantiles

100.0%	maximum	2.453
99.5%		2.453
97.5%		2.453
90.0%		1.969
75.0%	quartile	1.351
50.0%	median	-0.329
25.0%	quartile	-1.299
10.0%		-1.709
2.5%		-1.875
0.5%		-1.875
0.0%	minimum	-1.875

Moments

Mean	0.0173557
Std Dev	1.3884707
Std Err Mean	0.3585016
upper 95% Mean	0.7862652
lower 95% Mean	-0.751554
N	15

Figure A3. Model Fit Error For M1.1

B. FIT FOR M1.2

The results for the NABEM tactical situation 1 simulation for the M1.2 MoE, are feed into JMP. The fit model option is used to do an initial fit of the data using the surface response option.

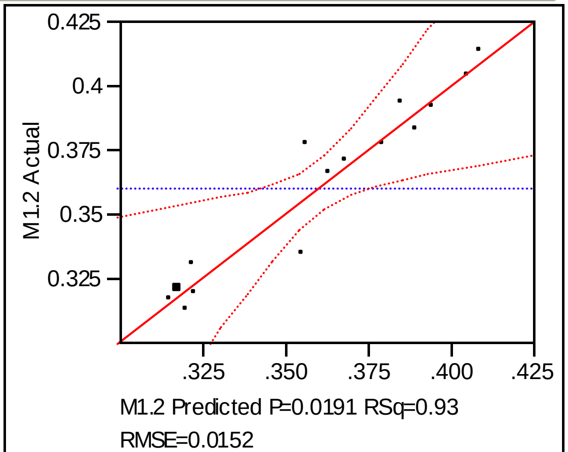
First is to determine if the model statistics indicate a good fit to the data. One, the RSquared and RSquared Adjusted values are 0.931 and 0.808 respectively, Figure A4 Generally anything higher than 0.80 would be acceptable and indicates a good model fit. Two, the Analysis of Variance the F statistic is 0.0191, which is well below the 0.05 for a desired 95% confidence level. The basic model statistics look good.

Second, a review of two key plots was preformed. One, the Actual by Predicted Plot, Figure A4, all the data points, with the exception of two points, fall within the 95% confidence lines (the dashed red line), indicating a good fit to the data. Two, the Residual by Predicted Plot, Figure A5, shows a fairly evenly shattering of the points. Some areas in the plot have holes, but that can be attributed to the small data set being analyzed, otherwise everything indicates a good model fit.

All indications show that the model listed in the Parameter Estimates in Figure A4 is a good model fit to the data.

For the model fit error analysis, Figure A6 shows the resulting distribution for the model percent error. The distribution does not look like a normal distribution, which is what would be expected. In addition, the mean is 0.061, which is close to 0.0, but the standard deviation is 2.28, which was much higher than desired. Based on the model fit error analysis, the model for M1.2 does not perform as well as would be expected from the initial analysis of the fit. This is due most likely to the small data set used for the analysis. An additional set of data points should be added to the analysis, to help better define the model. However, due to time and limited resources, that is not possible, and the fit will have to suffice with the caveat that the final analysis can only provide general trends, not qualitative answers.

Actual by Predicted Plot



Summary of Fit

RSquare	0.93161
RSquare Adj	0.808507
Root Mean Square Error	0.015241
Mean of Response	0.360433
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	0.01582198	0.001758	7.5677
Error	5	0.00116151	0.000232	Prob > F
C. Total	14	0.01698349		0.0191

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.1516173	0.117419	1.29	0.2531
Max Spd	0.0098716	0.006836	1.44	0.2083
Accel	0.1288625	0.183718	0.70	0.5143
Turn Dia	-0.000046	0.000065	-0.71	0.5112
Max Spd*Max Spd	-0.000073	0.000095	-0.77	0.4778
Max Spd*Accel	0.0003125	0.002694	0.12	0.9122
Accel*Accel	-0.195972	0.237618	-0.82	0.4471
Max Spd*Turn Dia	-5.767e-7	7.185e-7	-0.80	0.4586
Accel*Turn Dia	-0.000015	0.000036	-0.41	0.7000
Turn Dia*Turn Dia	1.8153e-8	1.69e-8	1.07	0.3318

Figure A4. Summary of Model Fit For M1.2

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Max Spd	1	1	0.00048440	2.0852	0.2083
Accel	1	1	0.00011429	0.4920	0.5143
Turn Dia	1	1	0.00011608	0.4997	0.5112
Max Spd*Max Spd	1	1	0.00013661	0.5881	0.4778
Max Spd*Accel	1	1	0.00000313	0.0135	0.9122
Accel*Accel	1	1	0.00015801	0.6802	0.4471
Max Spd*Turn Dia	1	1	0.00014964	0.6442	0.4586
Accel*Turn Dia	1	1	0.00003872	0.1667	0.7000
Turn Dia*Turn Dia	1	1	0.00026811	1.1542	0.3318

Residual by Predicted Plot

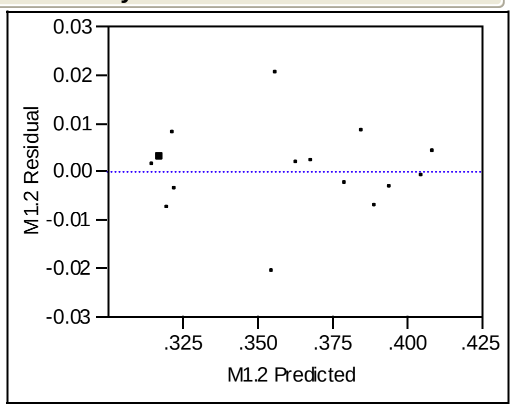
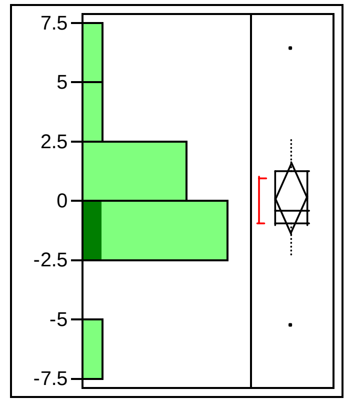


Figure A5. Summary of Model Fit For M1.2 (continued)

Error M1.2



Quantiles

100.0%	maximum	6.310
99.5%		6.310
97.5%		6.310
90.0%		4.029
75.0%	quartile	1.190
50.0%	median	-0.421
25.0%	quartile	-0.969
10.0%		-3.546
2.5%		-5.371
0.5%		-5.371
0.0%	minimum	-5.371

Moments

Mean	0.0616479
Std Dev	2.5828597
Std Err Mean	0.6668915
upper 95% Mean	1.4919879
lower 95% Mean	-1.368692
N	15

Figure A6. Model Fit Error For M1.2

C. FIT FOR M1.3

The results for the NABEM tactical situation 1 simulation for the M1.3 MoE, are feed into JMP. The fit model option is used to do an initial fit of the data using the surface response option.

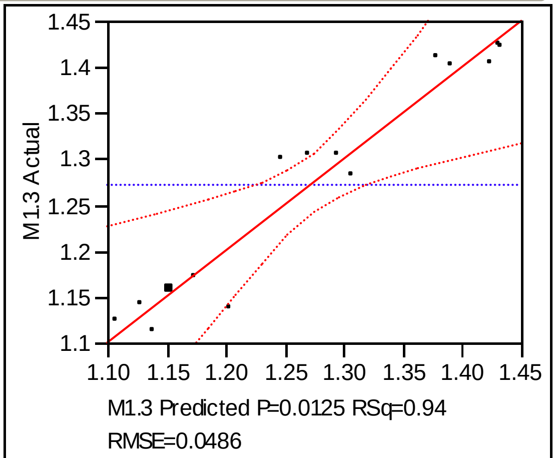
First is to determine if the model statistics indicate a good fit to the data. One, the RSquared and RSquared Adjusted values are 0.943 and 0.840 respectively, Figure A7 Generally anything higher than 0.80 would be acceptable and indicates a good model fit. Two, the Analysis of Variance the F statistic is 0.0125, which is well below the 0.05 for a desired 95% confidence level. The basic model statistics look good.

Second, a review of two key plots is preformed. One, the Actual by Predicted Plot, Figure A7, all the data points, with the exception of one point, fall within the 95% confidence lines (the dashed red line), indicating a good fit to the data. Two, the Residual by Predicted Plot, Figure A8, shows a fairly evenly shattering of the points. Some areas in the plot have holes, but that can be attributed to the small data set being analyzed, otherwise everything indicates a good model fit.

All indications show that the model listed in the Parameter Estimates in Figure A7 is a good model fit to the data.

For the model fit error analysis, Figure A9 shows the resulting distribution for the model percent error. The distribution does not look like a normal distribution, which is what would be expected. In addition, the mean is 0.054, which is close to 0.0, but the standard deviation is 2.38, which was much higher than desired. Based on the model fit error analysis, the model for M1.3 does not perform as well as would be expected from the initial analysis of the fit. This is due most likely to the small data set used for the analysis. An additional set of data points should be added to the analysis, to help better define the model. However, due to time and limited resources, that is not possible, and the fit will have to suffice with the caveat that the final analysis can only provide general trends, not qualitative answers.

Actual by Predicted Plot



Summary of Fit

RSquare	0.942996
RSquare Adj	0.840388
Root Mean Square Error	0.048598
Mean of Response	1.272847
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	0.19534854	0.021705	9.1903
Error	5	0.01180886	0.002362	Prob > F
C. Total	14	0.20715740		0.0125

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.1899542	0.374395	3.18	0.0246
Max Spd	-0.000472	0.021797	-0.02	0.9836
Accel	0.5637875	0.585794	0.96	0.3800
Turn Dia	-0.000239	0.000209	-1.15	0.3040
Max Spd*Max Spd	0.0001762	0.000303	0.58	0.5863
Max Spd*Accel	-0.000963	0.008591	-0.11	0.9152
Accel*Accel	-1.132083	0.757656	-1.49	0.1954
Max Spd*Turn Dia	0.0000011	0.000002	0.49	0.6447
Accel*Turn Dia	0.000024	0.000115	0.21	0.8423
Turn Dia*Turn Dia	5.2919e-8	5.388e-8	0.98	0.3711

Figure A7. Summary of Model Fit For M1.3

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Max Spd	1	1	0.00000111	0.0005	0.9836
Accel	1	1	0.00218766	0.9263	0.3800
Turn Dia	1	1	0.00309731	1.3114	0.3040
Max Spd*Max Spd	1	1	0.00079803	0.3379	0.5863
Max Spd*Accel	1	1	0.00002965	0.0126	0.9152
Accel*Accel	1	1	0.00527292	2.2326	0.1954
Max Spd*Turn Dia	1	1	0.00056785	0.2404	0.6447
Accel*Turn Dia	1	1	0.00010368	0.0439	0.8423
Turn Dia*Turn Dia	1	1	0.00227843	0.9647	0.3711

Residual by Predicted Plot

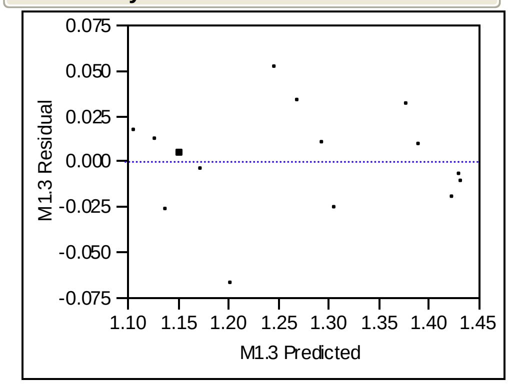
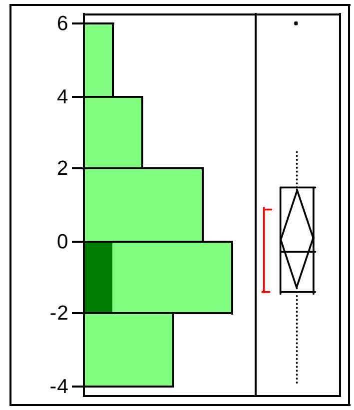


Figure A8. Summary of Model Fit For M1.3 (continued)

Error M1.3



Quantiles

100.0%	maximum	5.948
99.5%		5.948
97.5%		5.948
90.0%		3.814
75.0%	quartile	1.434
50.0%	median	-0.320
25.0%	quartile	-1.421
10.0%		-3.088
2.5%		-3.943
0.5%		-3.943
0.0%	minimum	-3.943

Moments

Mean	0.0535017
Std Dev	2.3775419
Std Err Mean	0.6138787
upper 95% Mean	1.3701406
lower 95% Mean	-1.263137
N	15

Figure A9. Model Fit Error For M1.3

APPENDIX B RESPONSE SURFACE MODEL FOR TACTICAL SITUATION 2

The following sections provide the general procedures to develop the response surface model fits for each measure of effectiveness for tactical situation 2. All analysis work is preformed using SAS's statistical modeling tool JMP (Version 5.1).

A. FIT FOR M2.1

The results for the NABEM tactical situation 1 simulation are feed into JMP. The fit model option is used to do an initial fit of the data using the surface response option.

First is to determine if the model statistics indicate a good fit to the data. One, the RSquared and RSquared Adjusted values are 0.879 and 0.662 respectively, Figure B1 Generally anything higher than 0.80 would be acceptable and indicates a good model fit. Two, the Analysis of Variance the F statistic is 0.0682, which is above the 0.05 for a desired 95% confidence level. The basic model statistics do not look great and deserve some more attention.

Second, a review of two key plots is preformed. One, the Actual by Predicted Plot, Figure B1, all the data points are falling within the 95% confidence lines (the dashed red line), indicating a good fit to the data. Two, the Residual by Predicted Plot, Figure B2, shows a fairly evenly shattering of the points. Some areas in the plot have holes, but that can be attributed to the small data set being analyzed, otherwise the plots indicate good model fit.

To fix the fit statistics, higher order terms (HOT) are added to the model. The two terms that have the most influence from the initial fit are (Turn Dia) and (Accel) (refer to the Pareto Plot in Figure B3). Running combinations of higher order terms using Turn Dia and Accel, the best results are achieved by adding the term [Turn Dia * Turn Dia * Accel]. The new RSquared and RSquared Adjusted values are 0.981 and 0.933 respectively, and the Analysis of Variance the F statistic is 0.0053, Figure B4.

The new Actual by Predicted Plot (Figure B4) and Residual by Predicted Plot (Figure B5) show the same similar characteristics as the initial fit

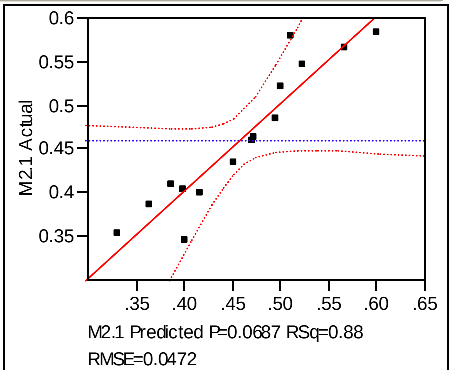
All indications show that the model listed in the Parameter Estimates in Figure B4 is a good model fit to the data. One additional test is needed to verify the accuracy of the model, a model fit error analysis.

The model fit error analysis checks how well the model fits the data points from the design of experiments. The model fit error, measured as the model percent error, is determined for each data point and the resulting distribution is evaluated against two error distribution criteria; a mean of approximately 0.0 and a standard deviation of less than 1.0 are desired. The model percent error is computed for each using the following equation:

$$\{[(\text{Predicted Value}) - (\text{M1.1 Actual})] / (\text{M1.1 Actual})\} \times 100$$

Figure 6 shows the resulting distribution for the model percent error. The distribution does not look like a normal distribution, which is what would be expected. In addition, the mean is 0.034, which is close to 0.0, but the standard deviation is 2.46, which is higher than desired. Based on the model fit error analysis, the model for M2.1 does not perform as well as would be expected from the initial analysis of the fit. This is due most likely to the small data set used for the analysis. An additional set of data points should be added to the analysis, to help better define the model. However, due to time and limited resources, that is not possible, and the fit will have to suffice with the caveat that the final analysis can only provide general trends, not qualitative answers.

Actual by Predicted Plot



Summary of Fit

RSquare	0.879522
RSquare Adj	0.662663
Root Mean Square Error	0.047242
Mean of Response	0.46052
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	0.08146320	0.009051	4.0557
Error	5	0.01115888	0.002232	Prob > F
C. Total	14	0.09262208		0.0687

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.562202	0.363946	1.54	0.1831
Max Spd	-0.021751	0.021189	-1.03	0.3517
Accel	-0.195535	0.569444	-0.34	0.7453
Turn Dia	0.0002962	0.000203	1.46	0.2042
Max Spd*Max Spd	0.0002767	0.000295	0.94	0.3907
Max Spd*Accel	0.0128187	0.008351	1.53	0.1854
Accel*Accel	-0.364444	0.736509	-0.49	0.6417
Max Spd*Turn Dia	-0.000002	0.000002	-1.03	0.3513
Accel*Turn Dia	0.0001381	0.000111	1.24	0.2700
Turn Dia*Turn Dia	-5.294e-8	5.237e-8	-1.01	0.3585

Figure B1. Summary of Initial Model Fit For M2.1

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Max Spd	1	1	0.00235164	1.0537	0.3517
Accel	1	1	0.00026315	0.1179	0.7453
Turn Dia	1	1	0.00475420	2.1302	0.2042
Max Spd*Max Spd	1	1	0.00196908	0.8823	0.3907
Max Spd*Accel	1	1	0.00525825	2.3561	0.1854
Accel*Accel	1	1	0.00054646	0.2449	0.6417
Max Spd*Turn Dia	1	1	0.00235641	1.0558	0.3513
Accel*Turn Dia	1	1	0.00343206	1.5378	0.2700
Turn Dia*Turn Dia	1	1	0.00228013	1.0217	0.3585

Residual by Predicted Plot

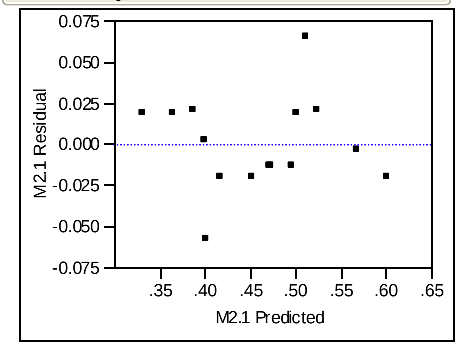


Figure B2. Summary of Initial Model Fit For M2.1 (continued)

Pareto Plot of Transformed Estimates

Term	Orthog Estimate
Accel	0.0450869
Turn Dia	0.0442541
Max Spd	-0.0207308
Max Spd*Accel	0.0187230
Accel*Turn Dia	0.0151263
Max Spd*Turn Dia	-0.0125337
Turn Dia*Turn Dia	-0.0123292
Accel*Accel	-0.0099742
Max Spd*Max Spd	0.0046810

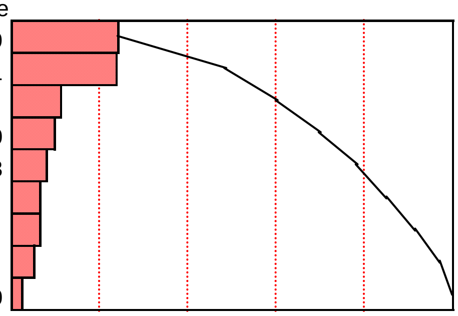
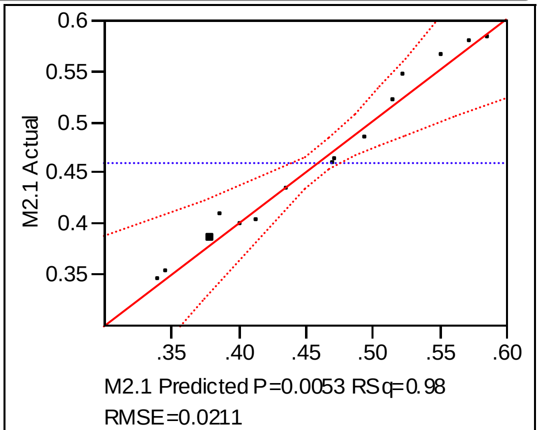


Figure B3. Pareto Plot For M2.1 Initial Fit

Actual by Predicted Plot



Summary of Fit

RSquare	0.980716
RSquare Adj	0.932507
Root Mean Square Error	0.021131
Mean of Response	0.46052
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	0.09083598	0.009084	20.3428
Error	4	0.00178610	0.000447	Prob > F
C. Total	14	0.09262208		0.0053

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.0954133	0.200116	5.47	0.0054
Max Spd	-0.021751	0.009478	-2.29	0.0834
Accel	-1.972906	0.464087	-4.25	0.0131
Turn Dia	-0.000418	0.00018	-2.32	0.0814
Max Spd*Max Spd	0.0002767	0.000132	2.10	0.1037
Max Spd*Accel	0.0128187	0.003735	3.43	0.0265
Accel*Accel	-0.364444	0.32944	-1.11	0.3307
Max Spd*Turn Dia	-0.000002	9.961e-7	-2.30	0.0832
Accel*Turn Dia	0.0025193	0.000522	4.83	0.0085
Turn Dia*Turn Dia	1.5116e-7	5.033e-8	3.00	0.0398
Turn Dia*Turn Dia*Accel	-6.803e-7	1.485e-7	-4.58	0.0102

Figure B4. Summary of Model Fit For M2.1 HOT

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Max Spd	1	1	0.00235164	5.2665	0.0834
Accel	1	1	0.00806974	18.0723	0.0131
Turn Dia	1	1	0.00239826	5.3709	0.0814
Max Spd*Max Spd	1	1	0.00196908	4.4098	0.1037
Max Spd*Accel	1	1	0.00525825	11.7759	0.0265
Accel*Accel	1	1	0.00054646	1.2238	0.3307
Max Spd*Turn Dia	1	1	0.00235641	5.2772	0.0832
Accel*Turn Dia	1	1	0.01039588	23.2817	0.0085
Turn Dia*Turn Dia	1	1	0.00402745	9.0195	0.0398
Turn Dia*Turn Dia*Accel	1	1	0.00937278	20.9905	0.0102

Residual by Predicted Plot

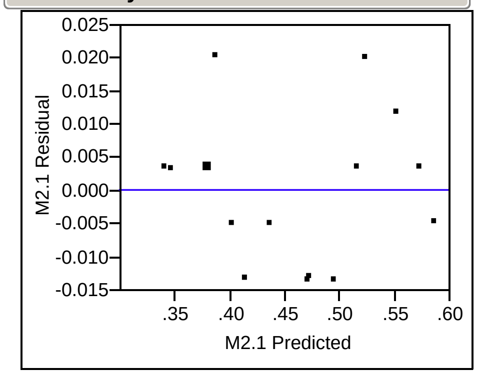
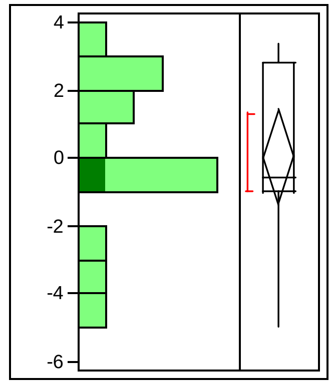


Figure B5. Summary of Model Fit For M2.1 HOT (continued)

Error M2.1 HOT



Quantiles

100.0%	maximum	3.314
99.5%		3.314
97.5%		3.314
90.0%		3.099
75.0%	quartile	2.790
50.0%	median	-0.587
25.0%	quartile	-0.984
10.0%		-4.176
2.5%		-4.961
0.5%		-4.961
0.0%	minimum	-4.961

Moments

Mean	0.0339701
Std Dev	2.4615782
Std Err Mean	0.6355768
upper 95% Mean	1.3971467
lower 95% Mean	-1.329206
N	15

Figure B6. Model Fit Error For M2.1 HOT

B. FIT FOR M2.2

The results for the NABEM tactical situation 2 simulations for the M2.2 MoE, are feed into JMP. The fit model option is used to do an initial fit of the data using the surface response option.

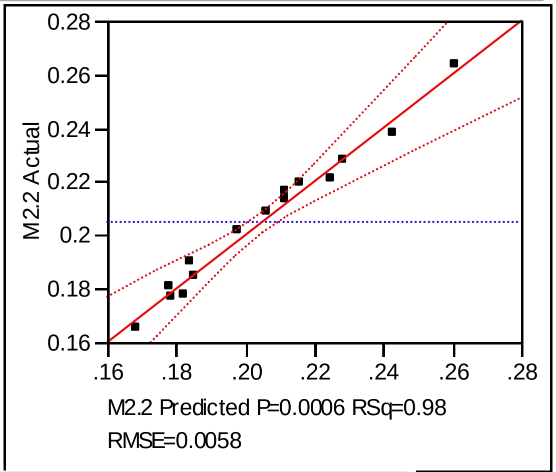
First is to determine if the model statistics indicate a good fit to the data. One, the RSquared and RSquared Adjusted values are 0.984 and 0.953 respectively, Figure B4 Generally anything higher than 0.80 would be acceptable and indicates a good model fit. Two, the Analysis of Variance the F statistic is 0.0006, which is well below the 0.05 for a desired 95% confidence level. The basic model statistics look good.

Second, a review of two key plots is preformed. One, the Actual by Predicted Plot, Figure B4, all the data points fall within the 95% confidence lines (the dashed red line), indicating a good fit to the data. Two, the Residual by Predicted Plot, Figure B5, shows a fairly evenly shattering of the points. Some areas in the plot have holes, but that can be attributed to the small data set being analyzed, otherwise everything indicates a good model fit.

All indications show that the model listed in the Parameter Estimates in Figure B4 is a good model fit to the data.

For the model fit error analysis, Figure B6 shows the resulting distribution for the model percent error. The distribution does not look like a normal distribution, which is what would be expected. In addition, the mean is 0.035, which is close to 0.0, but the standard deviation is 1.73, which is much higher than desired. Based on the model fit error analysis, the model for M2.2 does not perform as well as would be expected from the initial analysis of the fit. This is due most likely to the small data set used for the analysis. An additional set of data points should be added to the analysis, to help better define the model. However, due to time and limited resources, that is not possible, and the fit will have to suffice with the caveat that the final analysis can only provide general trends, not qualitative answers.

Actual by Predicted Plot



Summary of Fit

RSquare	0.983524
RSquare Adj	0.953868
Root Mean Square Error	0.005753
Mean of Response	0.205393
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	0.00987774	0.001098	33.1639
Error	5	0.00016547	0.000033	Prob > F
C. Total	14	0.01004321		0.0006

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.4019033	0.044319	9.07	0.0003
Max Spd	-0.015339	0.00258	-5.94	0.0019
Accel	-0.08226	0.069343	-1.19	0.2888
Turn Dia	0.0000437	0.000025	1.77	0.1372
Max Spd*Max Spd	0.0002244	0.000036	6.26	0.0015
Max Spd*Accel	0.0064187	0.001017	6.31	0.0015
Accel*Accel	-0.267639	0.089687	-2.98	0.0307
Max Spd*Turn Dia	-0.000001	2.712e-7	-3.94	0.0110
Accel*Turn Dia	0.0000642	0.000014	4.74	0.0052
Turn Dia*Turn Dia	-1.699e-9	6.378e-9	-0.27	0.8006

Figure B7. Summary of Model Fit For M2.2

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Max Spd	1	1	0.00116958	35.3413	0.0019
Accel	1	1	0.00004657	1.4073	0.2888
Turn Dia	1	1	0.00010355	3.1288	0.1372
Max Spd*Max Spd	1	1	0.00129537	39.1420	0.0015
Max Spd*Accel	1	1	0.00131841	39.8384	0.0015
Accel*Accel	1	1	0.00029471	8.9052	0.0307
Max Spd*Turn Dia	1	1	0.00051360	15.5195	0.0110
Accel*Turn Dia	1	1	0.00074305	22.4527	0.0052
Turn Dia*Turn Dia	1	1	0.00000235	0.0709	0.8006

Residual by Predicted Plot

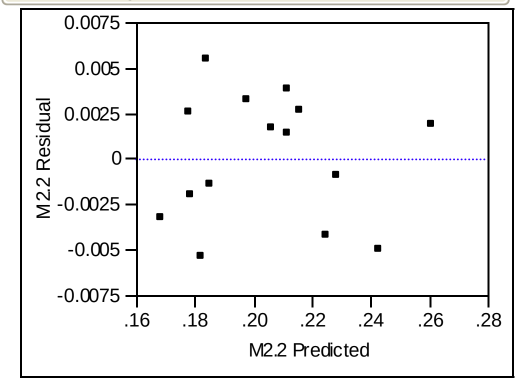
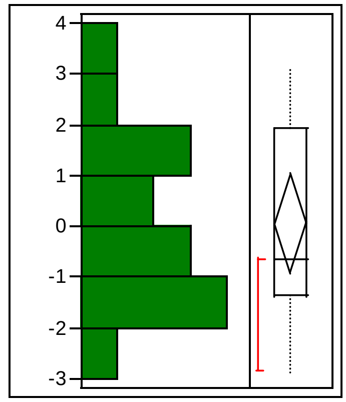


Figure B8. Summary of Model Fit For M2.2 (continued)

Error M2.2



Quantiles

100.0%	maximum	3.054
99.5%		3.054
97.5%		3.054
90.0%		2.484
75.0%	quartile	1.916
50.0%	median	-0.652
25.0%	quartile	-1.366
10.0%		-2.199
2.5%		-2.849
0.5%		-2.849
0.0%	minimum	-2.849

Moments

Mean	0.0347726
Std Dev	1.7341869
Std Err Mean	0.4477651
upper 95% Mean	0.9951333
lower 95% Mean	-0.925588
N	15

Figure B9. Model Fit Error For M2.2

C. FIT FOR M2.3

The results for the NABEM tactical situation 2 simulations for the M2.3 MoE, are feed into JMP. The fit model option is used to do an initial fit of the data using the surface response option.

First is to determine if the model statistics indicate a good fit to the data. One, the RSquared and RSquared Adjusted values are 0.892 and 0.698 respectively, Figure B10 Generally anything higher than 0.80 would be acceptable and indicates a good model fit.

Two, the Analysis of Variance the F statistic is 0.0539, which is above the 0.05 for a desired 95% confidence level. The basic model statistics do not look great and deserve some more attention.

Second, a review of two key plots is preformed. One, the Actual by Predicted Plot, Figure B10, all the data points, with the exception of two points, fall within the 95% confidence lines (the dashed red line), indicating a good fit to the data. Two, the Residual by Predicted Plot, Figure B11, shows a fairly evenly shattering of the points. Some areas in the plot have holes, but that can be attributed to the small data set being analyzed, otherwise everything indicates a good model fit.

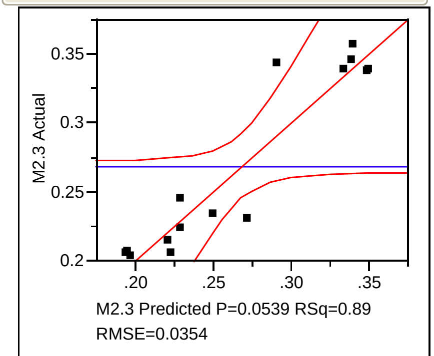
To fix the fit statistics, higher order terms are added to the model. The two terms that have the most influence from the initial fit are (Turn Dia) and (Accel) (refer to the Pareto Plot in Figure B12). Running combinations of higher order terms using Turn Dia and Accel, the best results are achieved by adding the term [Turn Dia * Turn Dia * Accel]. The new RSquared and RSquared Adjusted values are 0.987 and 0.954 respectively, and the Analysis of Variance the F statistic was 0.0025, Figure B13.

The new Actual by Predicted Plot (Figure B13) and Residual by Predicted Plot (Figure B11) show the same similar characteristics as for the initial fit

All indications show that the model listed in the Parameter Estimates in Figure B13 was a good model fit to the data.

For the model fit error analysis, Figure B15 shows the resulting distribution for the model percent error. The distribution does not look like a normal distribution, which is what would be expected. In addition, the mean is 0.035, which is close to 0.0, but the standard deviation is 1.73, which was much higher than desired. Based on the model fit error analysis, the model for M2.2 does not perform as well as would be expected from the initial analysis of the fit. This is due most likely to the small data set used for the analysis. An additional set of data points should be added to the analysis, to help better define the model. However, due to time and limited resources, that is not possible, and the fit will have to suffice with the caveat that the final analysis can only provide general trends, not qualitative answers.

Actual by Predicted Plot



Summary of Fit

RSquare	0.892177
RSquare Adj	0.698097
Root Mean Square Error	0.035382
Mean of Response	0.268027
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	0.05179362	0.005755	4.5969
Error	5	0.00625943	0.001252	Prob > F
C. Total	14	0.05805305		0.0539

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.6479478	0.27258	2.38	0.0634
Max Spd	-0.018509	0.01587	-1.17	0.2961
Accel	-0.494212	0.426489	-1.16	0.2989
Turn Dia	0.0001293	0.000152	0.85	0.4339
Max Spd*Max Spd	0.0001578	0.000221	0.72	0.5066
Max Spd*Accel	0.0021875	0.006255	0.35	0.7408
Accel*Accel	0.7844444	0.551614	1.42	0.2143
Max Spd*Turn Dia	-6.667e-9	0.000002	-0.00	0.9970
Accel*Turn Dia	-0.000004	0.000083	-0.04	0.9666
Turn Dia*Turn Dia	-3.666e-8	3.923e-8	-0.93	0.3929

Figure B10. Summary of Initial Model Fit For M2.3

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Max Spd	1	1	0.00170293	1.3603	0.2961
Accel	1	1	0.00168103	1.3428	0.2989
Turn Dia	1	1	0.00090551	0.7233	0.4339
Max Spd*Max Spd	1	1	0.00064013	0.5113	0.5066
Max Spd*Accel	1	1	0.00015313	0.1223	0.7408
Accel*Accel	1	1	0.00253174	2.0223	0.2143
Max Spd*Turn Dia	1	1	0.00000002	0.0000	0.9970
Accel*Turn Dia	1	1	0.00000242	0.0019	0.9666
Turn Dia*Turn Dia	1	1	0.00109357	0.8735	0.3929

Residual by Predicted Plot

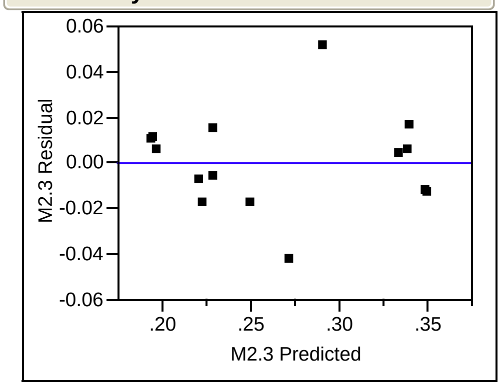


Figure B11. Summary of Initial Model Fit For M2.3 (continued)

Pareto Plot of Transformed Estimates

Term	Orthog Estimate
Max Spd	-0.0556851
Accel*Accel	0.0110111
Max Spd*Max Spd	0.0094658
Turn Dia*Turn Dia	-0.0085384
Accel	0.0076097
Max Spd*Accel	0.0031950
Accel*Turn Dia	-0.0004017
Turn Dia	-0.0002286
Max Spd*Turn Dia	-0.0000365

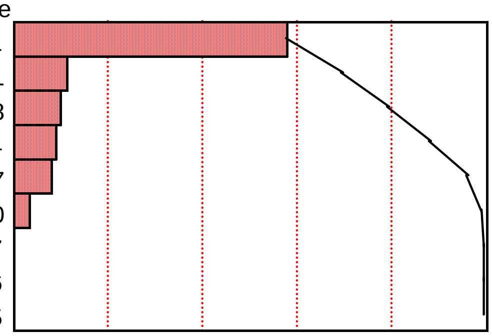
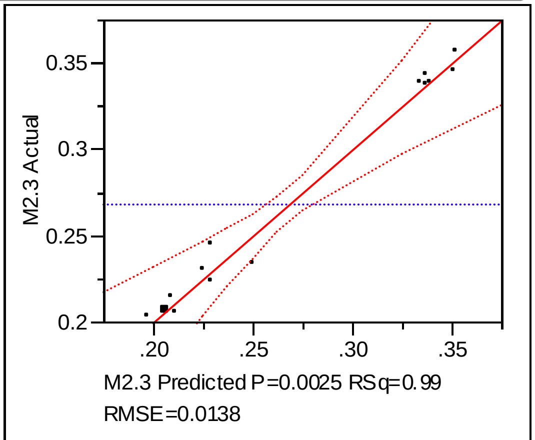


Figure B12. Pareto Plot For M2.3Initial Fit

Actual by Predicted Plot



Summary of Fit

RSquare	0.986821
RSquare Adj	0.953873
Root Mean Square Error	0.01383
Mean of Response	0.268027
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	0.05728796	0.005729	29.9509
Error	4	0.00076509	0.000191	Prob > F
C. Total	14	0.05805305		0.0025

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.6544028	0.215907	7.66	0.0016
Max Spd	-0.080039	0.013049	-6.13	0.0036
Accel	-3.849062	0.647772	-5.94	0.0040
Turn Dia	0.0001293	0.000059	2.18	0.0952
Max Spd*Max Spd	0.0010368	0.000185	5.60	0.0050
Max Spd*Accel	0.2072875	0.038346	5.41	0.0057
Accel*Accel	0.7844444	0.215615	3.64	0.0220
Max Spd*Turn Dia	-6.667e-9	6.52e-7	-0.01	0.9923
Accel*Turn Dia	-0.000004	0.000033	-0.11	0.9159
Turn Dia*Turn Dia	-3.666e-8	1.533e-8	-2.39	0.0751
Max Spd*Max Spd*Accel	-0.00293	0.000547	-5.36	0.0058

Figure B13. Summary of Model Fir M2.3 HOT

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Max Spd	1	1	0.00719612	37.6223	0.0036
Accel	1	1	0.00675334	35.3074	0.0040
Turn Dia	1	1	0.00090551	4.7341	0.0952
Max Spd*Max Spd	1	1	0.00598788	31.3054	0.0050
Max Spd*Accel	1	1	0.00558935	29.2219	0.0057
Accel*Accel	1	1	0.00253174	13.2363	0.0220
Max Spd*Turn Dia	1	1	0.00000002	0.0001	0.9923
Accel*Turn Dia	1	1	0.00000242	0.0127	0.9159
Turn Dia*Turn Dia	1	1	0.00109357	5.7173	0.0751
Max Spd*Max Spd*Accel	1	1	0.00549434	28.7251	0.0058

Residual by Predicted Plot

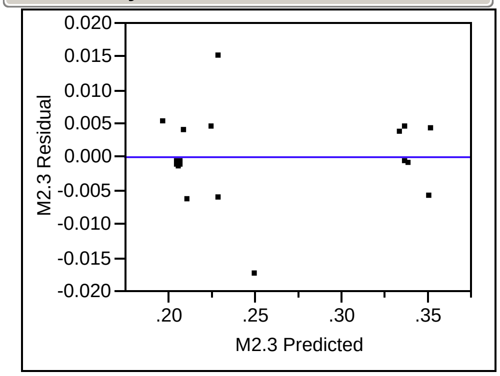
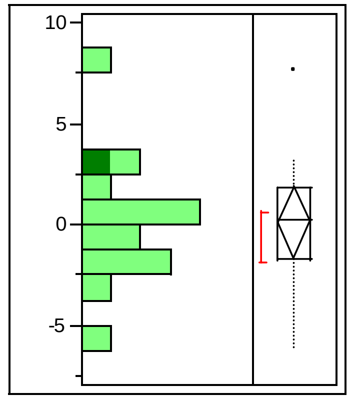


Figure B14. Summary of Model Fit For M2.3 HOT (continued)

Error M2.3 HOT



Quantiles

100.0%	maximum	7.533
99.5%		7.533
97.5%		7.533
90.0%		4.893
75.0%	quartile	1.744
50.0%	median	0.213
25.0%	quartile	-1.795
10.0%		-3.981
2.5%		-6.124
0.5%		-6.124
0.0%	minimum	-6.124

Moments

Mean	0.072618
Std Dev	3.086312
Std Err Mean	0.7968823
upper 95% Mean	1.7817607
lower 95% Mean	-1.636525
N	15

Figure B15. Model Fit Error For M2.3 HOT

D. FIT FOR M2.4

The results for the NABEM tactical situation 2 simulations for the M2.4 MoE, are feed into JMP. The fit model option was used to do an initial fit of the data using the surface response option.

First is to determine if the model statistics indicate a good fit to the data. One, the RSquared and RSquared Adjusted values are 0.956 and 0.877 respectively, Figure B16 Generally anything higher than 0.80 would be acceptable and indicates a good model fit.

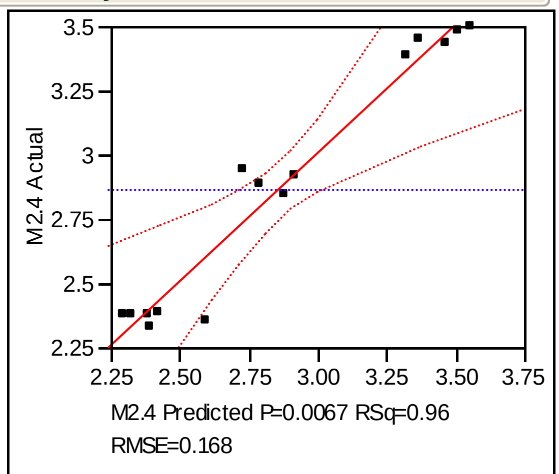
Two, the Analysis of Variance the F statistic is 0.0067, which is well below the 0.05 for a desired 95% confidence level. The basic model statistics look good.

Second, a review of two key plots is preformed. One, the Actual by Predicted Plot, Figure B16, all the data points, with the exception of two points, fall within the 95% confidence lines (the dashed red line), indicating a good fit to the data. Two, the Residual by Predicted Plot, Figure B17, shows a fairly evenly shattering of the points. Some areas in the plot have holes, but that can be attributed to the small data set being analyzed, otherwise everything indicates a good model fit.

All indications show that the model listed in the Parameter Estimates in Figure B10 is a good model fit to the data.

For the model fit error analysis, Figure B18 shows the resulting distribution for the model percent error. The distribution does not look like a normal distribution, which is what would be expected. In addition, the mean is 0.141, which is close to 0.0, but the standard deviation is 3.85, which was much higher than desired. Based on the model fit error analysis, the model for M2.2 does not perform as well as would be expected from the initial analysis of the fit. This is due most likely to the small data set used for the analysis. An additional set of data points should be added to the analysis, to help better define the model. However, due to time and limited resources, that is not possible, and the fit will have to suffice with the caveat that the final analysis can only provide general trends, not qualitative answers.

Actual by Predicted Plot



Summary of Fit

RSquare	0.95616
RSquare Adj	0.877249
Root Mean Square Error	0.167962
Mean of Response	2.86704
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	3.0764861	0.341832	12.1169
Error	5	0.1410564	0.028211	Prob > F
C. Total	14	3.2175425		0.0067

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.8127759	1.293965	2.17	0.0818
Max Spd	-0.034566	0.075335	-0.46	0.6656
Accel	2.0120896	2.024589	0.99	0.3659
Turn Dia	-0.000667	0.000722	-0.92	0.3976
Max Spd*Max Spd	0.0013263	0.001047	1.27	0.2612
Max Spd*Accel	-0.011356	0.029692	-0.38	0.7178
Accel*Accel	-3.271806	2.61857	-1.25	0.2668
Max Spd*Turn Dia	-5.117e-7	0.000008	-0.06	0.9510
Accel*Turn Dia	7.5e-7	0.000396	0.00	0.9986
Turn Dia*Turn Dia	1.8814e-7	1.862e-7	1.01	0.3587

Figure B16. Summary of Model Fit For M2.4

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Max Spd	1	1	0.00593924	0.2105	0.6656
Accel	1	1	0.02786401	0.9877	0.3659
Turn Dia	1	1	0.02411475	0.8548	0.3976
Max Spd*Max Spd	1	1	0.04523176	1.6033	0.2612
Max Spd*Accel	1	1	0.00412686	0.1463	0.7178
Accel*Accel	1	1	0.04404224	1.5612	0.2668
Max Spd*Turn Dia	1	1	0.00011781	0.0042	0.9510
Accel*Turn Dia	1	1	0.00000010	0.0000	0.9986
Turn Dia*Turn Dia	1	1	0.02879876	1.0208	0.3587

Residual by Predicted Plot

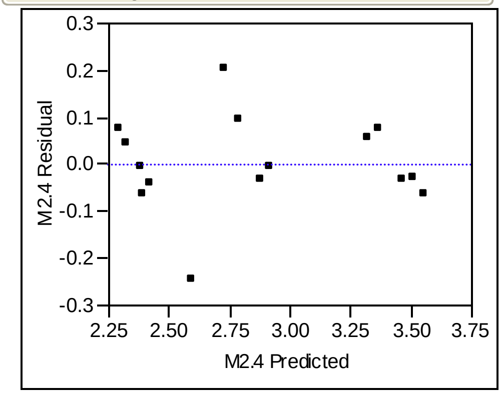
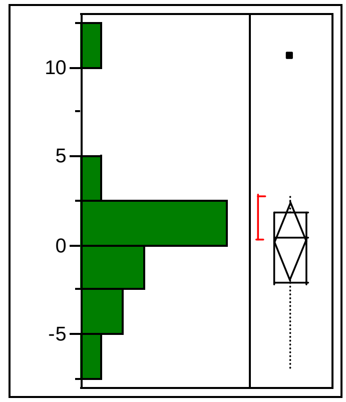


Figure B17. Summary of Model Fit For M2.4 (continued)

Error M2.4



Quantiles

100.0%	maximum	10.58
99.5%		10.58
97.5%		10.58
90.0%		5.88
75.0%	quartile	1.83
50.0%	median	0.39
25.0%	quartile	-2.18
10.0%		-4.66
2.5%		-6.90
0.5%		-6.90
0.0%	minimum	-6.90

Moments

Mean	0.1400942
Std Dev	3.8536282
Std Err Mean	0.9950025
upper 95% Mean	2.2741623
lower 95% Mean	-1.993974
N	15

Figure B18. Model Fit Error For M2.4

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